Operating Storage-Augmented Energy Systems in Industrial and Residential Applications

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Last but most importantly, I must thank my beloved family for the continuous support throughout all these years. I assume every PhD student faces countless stressful times with no end in sight during his journey. For me, it has always been the family on whose support I knew I could count. Above all, I would like to express my gratitude to my beloved Alexandra for bearing with me during very stressful situations in the past year.

With this dissertation, I hope that I have contributed to advancing the further integration of renewable energy sources into modern energy systems. Throughout my journey, I discovered an endless amount of research opportunities with even better prospects, and often questioned myself if I had chosen the right path. In the end, Friedrich Nietzsche once wrote so eloquently about the melancholy in everything that has been finished:

> *„Die Melancholie alles Fertigen! Wenn man sich sein Haus fertig gebaut hat,*
> *merkt man, unversehens etwas dabei gelernt zu haben,*
> *das man schlechterdings hätte wissen müssen, bevor man zu bauen anfing“*
> *(Friedrich Nietzsche, Jenseits von Gut und Böse, 277)*

Frankfurt, Oktober 2018 Timm Weitzel

Zusammenfassung

Die vorliegende kumulative Dissertation untersucht den Betrieb speichergestützter Energiesysteme und ihre Interaktion mit den übergeordneten Stromnetzen. Ein speichergestütztes Energiesystem im Sinne dieser Arbeit ist definiert als ein elektrisches Energiespeichersystem in unmittelbarer Umgebung von lokalen, steuerbaren Konsumenten und/oder dezentralen Energieerzeugungsanlagen. Alle Komponenten befinden sich unter gemeinsamer, lokaler Steuerung. Diese Arbeit umfasst vier Artikel, die in verschiedenen wissenschaftlichen Zeitschriften bzw. Konferenzbänden veröffentlicht wurden und die sich jeweils mit unterschiedlichen Aspekten der folgenden vier Forschungsfragen (FF) beschäftigen:

FF1: *Was ist der aktuelle Stand der Forschung zur mathematischen Modellierung von Entscheidungsproblemen im Betrieb speichergestützter Energiesysteme?*

FF2: *Wie beeinflussen sich thermische und elektrische Energiespeichersysteme in ihrem Betrieb innerhalb eines hybriden Energiesystems und wie sollte das Gesamtsystem in diesem Fall betrieben werden?*

FF3: *Welche Modelle eignen sich, um Batteriealterungskosten in das Betriebsproblem zu integrieren, und wie beeinflusst dieser Kostenfaktor den optimalen Betrieb des speichergestützten Energiesystems?*

FF4: *Welche Effekte entstehen aus der Integration von elektrischen Energiespeichersystemen in industrielle Produktionseinrichtungen und wie beeinflusst dies deren Fähigkeit, dem Netz lokale Flexibilitätsoptionen bereitzustellen?*

Die einzelnen Artikel unterscheiden sich abgesehen von ihrer inhaltlichen Ausrichtung auch in der jeweils angewendeten Methodik. Artikel 1 stellt einen systematischen Literaturüberblick zum Betrieb von Energiespeichersystemen in stationären Anwendungen dar. Artikel 2 und 4 entwickeln mathematische Modelle zur Entscheidungsunterstützung für Wohnsiedlungs- und Industrieanwendungen und präsentieren eine analytische Lösung. Artikel 3 formuliert einen konzeptionellen Rahmen zur Identifikation und Realisierung von Flexibilitätsansätzen in der industriellen Produktion. Die folgenden Abschnitte fassen die vier Artikel kurz zusammen.

Der systematische und umfassende Literaturüberblick in Artikel 1 entwickelt eine Übersicht über den aktuellen Stand der Forschung in diesem Bereich. Der Fokus dieses Beitrags liegt dabei auf den betrachteten Kontexten der speichergestützten Systeme, ihrer mathematischen Modellierung und den damit verbundenen Lösungsansätzen zur Definition einer Betriebsstrategie. Insbesondere auf dem Gebiet der Batteriealterung wird herausgearbeitet, welche Modellierungsansätze bisher existieren und auf welchen Gebieten weitere Forschung notwendig erscheint. Auf Basis einer Synthese der Ergebnisse der Literaturrecherche werden abschließend sieben Vorschläge zu zukünftigen Forschungsrichtungen herausgearbeitet, welche zum Teil in den folgenden Artikeln aufgegriffen werden.

Artikel 2 untersucht den Betrieb eines speichergestützten hybriden Energiesystems in einem Wohnsiedlungskontext unter Berücksichtigung von Batteriealterungskosten und greift damit einen von den in Artikel 1 identifizierten Vorschlägen auf. Untersucht wird in diesem Artikel die Rolle eines lokalen Energieversorgers, der, bezogen auf die Wohnsiedlung, verantwortlich für die Erfüllung der elektrischen und thermischen Bedarfe der Siedlungsbewohner ist und dafür über die lokalen Erzeugungseinheiten, d.h. eine Photovoltaik-Anlage, ein Blockheizkraftwerk und einen Gas-Heizkessel sowie einen thermischen Speicher und einen Batteriespeicher verfügen kann. Der lokale Energieversorger ist bestrebt, die Versorgung der Wohnsiedlung effizient zu gestalten und dazu die Nutzungsrate des Blockheizkraftwerks zu maximieren. Obwohl das Blockheizkraftwerk thermische und elektrische Energie in festen Verhält-

nissen produziert, treten thermische und elektrische Bedarfe nicht zwingend zeitgleich auf. Eine Entkopplung von Erzeugung und Verbrauch kann durch den Einsatz der Speichersysteme erreicht werden. Insbesondere das Batteriespeichersystem unterliegt allerdings nutzungsabhängigen, nicht-linearen Alterungseffekten, die der lokale Betreiber berücksichtigen muss. In einer kurzen, ergänzenden Literaturrecherche werden zunächst aktuelle Arbeiten zur Unterstützung des Betriebs von Energiesystemen unter Berücksichtigung von Batteriealterungseffekten zusammengefasst. Obwohl das Entscheidungsproblem des lokalen Energieversorgers schon weitläufig in der Literatur betrachtet wurde, ist die Integration der Batteriealterungseffekte noch unterrepräsentiert. Artikel 2 adressiert diese Lücke und stellt zunächst eine Formulierung des Entscheidungsproblems als gemischt-ganzzahliges lineares Optimierungsproblem auf. Dieses wird anschließend um das linearisierte Batteriealterungsmodell ergänzt und durch die Anwendung eines entsprechenden Lösungsverfahren analytisch gelöst. In rechnergestützten Untersuchungen wird gezeigt, dass sich der optimale Einsatz der Batterie gravierend zwischen den Modellen mit und ohne Berücksichtigung der Batteriealterung unterscheidet. Im Weiteren geht Artikel 2 noch auf die Abhängigkeit zwischen den thermischen und elektrischen Teilsystemen ein und zeigt, dass sich elektrische und thermische Speichersysteme in ihrer Rolle ergänzen und überschneiden und daher die Gesamtauslegung beeinflussen.

Artikel 3 und Artikel 4 fokussieren Anwendungen im Rahmen industrieller Konsumenten. Artikel 3 folgt der Idee, dass Produktionseinrichtungen eine Vielzahl von Möglichkeiten haben, um ihren elektrischen Bedarf bezüglich Zeit und Volumen anzupassen. Diese ermöglichen es ihnen, den Netzbetreibern benötigte Flexibilitätsoptionen anzubieten. Hierzu wird in diesem Artikel ein konzeptionelles Rahmenwerk für eine energiebewusste Perspektive auf Produktionseinrichtungen entwickelt, um die verschiedenen Flexibilitätsoptionen zu identifizieren. Neben dem zentralen Produktionssystem, dessen Energiebezug durch Anpassung der Produktionsplanung veränderbar ist, richtet sich dabei der Fokus insbesondere auf unterstützende Systeme wie Flurförderzeuge, lokale Energiewandlungsprozess der technischen Gebäudeausstattung oder ähnliches. Viele dieser Teilsysteme sind bereits mit Energiespeichern ausgestattet, stellen solche dar oder zeigen ein speicherähnliches Verhalten.

Artikel 4 bildet den Abschluss dieser Arbeit und präsentiert eine vertiefende Analyse der in Artikel 3 angedeuteten Flexibilitätspotentiale in industriellen Produktionseinrichtungen in Kombination mit unterstützenden elektrischen Speichersystemen. Dieser Artikel betrachtet dazu die Produktionseinrichtung einer diskreten Fertigung in Kombination mit einem Batteriespeichersystem. Zunächst werden die Herausforderungen an eine solche Einrichtungen aufgezeigt, wenn diese Flexibilität im Rahmen eines aktiven Lastmanagements anbieten. Einige bestehende Programme erfordern es, dass unabhängige Dritte direkten Einfluss auf einzelne Verbraucher nehmen (z.B. um diese abzuschalten oder zu drosseln). Dies stellt für Betreiber einer solchen Produktionseinrichtung eine große Einschränkung und einen schwerwiegenden Eingriff in ihre Integrität dar. Artikel 4 schlägt daher ein alternatives Programm vor, in dem die Betreiber der Produktionseinrichtung alternative Verbrauchsszenarien vorab analytisch ermitteln und diese als mögliche Lastveränderungen an den Netzbetreiber kommunizieren. Dieser kann anschließend im Bedarfsfall auf dieses Angebot zurückgreifen und eine entsprechende Auswahl treffen. Aufbauend auf diesem Programm formuliert Artikel 4 das Entscheidungsproblem als gemischt-ganzzahliges Optimierungsproblem, um die verschiedenen Verbrauchsszenarien zu ermitteln. Dazu wird in einem zweistufigen Verfahren zunächst die die Durchlaufzeit minimierende Basislösung ermittelt, um anschließend davon abweichende Szenarien zu erzeugen. Diese Szenarien werden abschließend in einer Lastreduktionskurve als potentielles Kommunikationsinstrument zusammengefasst. Das Batteriespeichersystem wird in diesem Gesamtproblem dazu verwendet, die Potentiale der Fabrik zu erhöhen. In einem numerischen Beispiel werden die Effekte der einzelnen Vorgänge untersucht und die Vorzüge des batteriegestützten Gesamtsystems aufgezeigt.

Abstract

This cumulative dissertation investigates the operation of storage-augmented energy systems and their interaction with the overall energy system. A storage-augmented energy system, in this context, is defined as an electric energy storage system in close proximity to consumers and distributed generation units under joint control. This work consists of four papers published in scientific, peer-reviewed journals and conference proceedings that aim to answer the following Research Questions (RQs):

RQ1: *What is the status of research of mathematical decision support models for operating storage-augmented energy systems?*

RQ2: *How do thermal and electrical energy storage systems in hybrid energy systems influence each other, and how does their interaction influence the way the superordinate system should be operated?*

RQ3: *Which models are suitable to include battery aging costs into the operation problem, and how does this cost-factor change the way the storage-augmented energy system should be operated?*

RQ4: *To what extent does including an EESS into an industrial production facility enhance the flexibility offering to the overall energy system?*

All four papers focus on various combinations of the above RQs, and apply different research methodologies to address them. Paper 1 begins with a systematic and comprehensive literature review on the current status of research of energy management for storage-augmented systems in stationary applications. The paper first develops a conceptual framework, which is then used to structure and discuss the relevant literature. Paper 1 concludes with a set of propositions for future research based on the identified research gaps, and hence prepares Papers 2 to 4. Paper 2 und Paper 4 develop mathematical models for operating storage-augmented energy systems in residential and industrial applications, respectively, and discuss the results of computational studies on exemplary configurations. Paper 3, in contrast, formulates a conceptual framework on demand-side flexibility measures in industrial production facilities as a preliminary work for Paper 4. In the following, the different research areas of Papers 1 to 4 are outlined in more detail, and the specific research gaps addressed by the four papers are explained.

The systematic and comprehensive literature review presented in Paper 1 develops an overall view on the current status of research in the field (RQ1). Paper 1 provides an introduction to energy management of electric energy storage systems in general, and the multifarious aspects to be considered when operating stationary systems in particular. Research in this field has received more and more attention in recent years. The vast amount of publications on the management of electric energy storage systems, especially those that appeared in the last ten years, has created a need for a structured review and classification of existing research. Although several papers reviewing the matter have been published, the review in Paper 1 differs from existing research in terms of its focus on mathematical models and its systematic review approach. In the synthesis of the reviewed publications, Paper 1 outlines propositions for future research, which were partially addressed in Papers 2 to 4.

Paper 2 analyzes operations of a storage-augmented, hybrid residential microgrid. The paper contributes to research by investigating the case of a local energy supplier. The local energy supplier is responsible for meeting local hybrid, i.e. electrical and thermal, energy demands while interacting with the grid at real-time pricing. The major benefit for the energy supplier comes from efficiently using non-renewable decentralized generation units by leveraging thermal energy storage systems and electric energy storage systems. Compared to classical, thermal power plants, distributed generation units utilize primary energy resources more efficiently as they offer the opportunity to use excess heat to serve local thermal demand. Gas-fired combined heat and power plants can operate at combined efficiencies ranging between 70 % and 80 %. This is well above the efficiency levels of conventional power plants without waste heat utilization that usually do not exceed 30 %. Thermal and electrical energy demand in hybrid systems are for the most part uncorrelated, whereas combined generation units generate thermal and electrical energy simultaneously in a fixed ratio. Therefore, in practice, combined generation units follow either electrical or thermal loads when operated heuristically. Two approaches have been applied in Paper 2 to respond to these challenges. On the on hand, optimization methods support economic and reliable operations of microgrids and have already attracted much attention among researchers and practitioners in recent years. On the other hand, hybrid energy storage systems, a combination of electric and thermal energy storage systems, can be applied to decouple both types of demands. Paper 2 first contributes to research by revisiting current work on optimization models for microgrids that include battery energy storage systems and take battery aging into account (RQ3). Most of current research has focused on using batteries to optimize energy systems for economic, ecological, and technical objectives, but barely considered battery aging in the optimization models. Especially battery aging models that consider specific usage conditions have been underrepresented. Paper 2 addresses this research gap by deriving a weighted cost model, considering both cyclical and calendrical aging components, from the domain-specific literature on battery lifetime prediction. The paper further integrates the piecewise-linearized battery aging model into a mixed-integer linear programming formulation for a hybrid microgrid application. The influence of the battery aging model formulation on microgrid operations in a cost-optimal schedule is illustrated in a computational study for a real-world example. Secondly, Paper 2 contributes to research by investigating the interdependencies of the thermal and electrical systems in a parameter study on component sizing. Sensitivities are investigated through selected key parameters and show that both storage types can significantly reduce the grid-provided energy without losing economic viability.

Paper 3 and Paper 4 put the spotlight on the industrial consumer. By size, the industrial sector was responsible for around 42.5% of world-wide electricity consumption in 2014. This entails a large potential for generating flexibility by demand-side management. Paper 3 addresses research efforts undertaken to tap this potential and to enable industrial consumers to offer short-term flexibility. Paper 3 fosters the idea that production facilities incorporate a versatile set of flexibility measures that enable them to modulate their electricity consumption time- and volume-wise and, as a result, to participate in respective flexibility markets. Paper 3 develops a conceptual framework for an energy-aware view on production facilities to identify the various resources of flexibility. Besides the production system, whose energy consumption is adjustable by changing the production schedule, there are many examples for additional resources of flexibility such as local generation, energy conversion systems, and other auxiliary systems, of which many show a storage-equivalent behavior. As a final note, the paper proposes a control architecture to coordinate the different sources of flexibility.

Paper 4 concludes this dissertation. The paper elaborates on the ideas outlined in Paper 3 and presents an in-depth analysis of a storage-augmented industrial production facility participating in demand response. For simplicity, this work concentrates on the production system and a co-located battery. Paper 4 outlines challenges for industrial consumers participating in demand response and provides an overview of the corresponding literature. For residential and commercial consumers, interdependencies between the scheduling of different applications (e.g., refrigerators or air conditioning equipment) are negligible and scheduling can be performed independently. Prior research has investigated various residential applications and to what extent they are compatible with demand response, e.g. for air conditioning, cloth dryers, or dishwashers. For industrial consumers, however, participating in demand response is more difficult as the scheduling of processes within facilities is often subject to many interdependencies.

While in many traditional demand response programs, system operators require direct control of single consumers for short-term flexibility, the aforementioned complexity within industrial consumers falsifies the appropriateness of such approaches and reveals the need for other solutions. In industrial applications, demand response thus requires sophisticated models that account for the influence of demand response on production processes and vice versa. Firstly, Paper 4 contributes to this research by proposing an incentive-based program according to which the facility operator determines alternative electricity consumption scenarios and communicates discrete load reduction potentials to the system operator without disclosing internal processes. Secondly, Paper 4 develops a flexible flow shop formulation for a discrete manufacturing process. A reference model is extended to account for the operating-mode-specific energy consumption of machines with specific consumption trajectories per product-machine-combination. A mixed-integer linear programming formulation is suggested to model and solve the problem in three stages. First, a baseline solution is developed by minimizing total weighted completion time. Then, based on the baseline solution, additional solutions with different responses to the demand response are calculated and a load reduction curve as a potential means of communication is established. Finally, the effects of using a battery to allow easy-to-apply and economically better responses are studied. A numerical example is provided and analyzed to give a zest of the suggested solution.

Outline

Table of Contents

List of Abbreviations

ACO	Ant Colony Optimization
ADP	Approximate Dynamic Programming
BAC	Battery Aging Cost
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CF	Cycles to Failure
CHP	Combined Heat and Power Plant
CR	Charge Rate
CS	Cuckoo Search
DC	Direct Current
DE	Differential Evolution
DG	Distributed Generation
DOD	Depth of Discharge
DP	Dynamic Programming
DR	Demand Response
DRP	Demand Response Period
DSM	Demand Side Management
DSO	Distribution System Operators
ECS	Energy Conversion Systems
EEPP	Energy Efficient Production Planning
EESS	Electric Energy Storage System
EEX	European Energy Exchange
EOL	End-Of-Life
EV	Electric Vehicle
FBESS	Flow Battery Energy Storage System
FESS	Flywheel Energy Storage System
FFS	Flexible Flow Shop
FO	Facility Operator
FS	Flow Shop
GA	Genetic Algorithms
HES	Hydrogen Energy Storage
HILES	Integrated Local Energy Supplier
HTR	Heater
IBP	Incentive-based Program
ILP	Integer Linear Programming
kW	Kilowatts
kWth	Thermal kilowatts
kWel	Electric kilowatts
kWh	Kilowatt-hours
LA	Lead acid
LFP	Lithium Iron Phosphate
LGS	Local (renewable) Generation Systems
LRC	Load Reduction Curve
MCS	Monte Carlo Simulation
MDP	Markov Decision Process
MG	Microgrid
MILP	Mixed Integer Linear Programming
min	Minutes
MINLP	Mixed Integer Non-Linear Programming
MPC	Model Predictive Control
NC	Network Charges
NMC	Lithium Nickel Manganese Cobalt Oxide
NRMSE	Normalized Root Mean Square Error
p.a.	Per Annum
PbAS	Production-bound Auxiliary Systems
PBP	Price-based Program
PF	Production Facilities
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydro Storage
PS	Production System
PSO	Particle Swarm Optimization
PV	Photovoltaic
PWL	Piecewise Linear
RA	Reference Area
RES	Renewable Energy Sources
RTP	Real Time Pricing
SA	Simulated Annealing
SC	Supercapacitors
SDP	Stochastic Dynamic Programming
SMES	Superconducting Magnetic Energy Storage
SO	System Operator
SOC	State of Charge
TESS	Thermal Energy Storage System
TOU	Time of Use Pricing
TWCT	Total Weighted Completion Time
UAS	Unbound Auxiliary Systems
WT	Wind Turbine

List of Figures

Chapter I. Introduction

Chapter II. [Paper 1]

Chapter III. [Paper 2]

Chapter IV. [Paper 3]

Chapter V. [Paper 4]

List of Tables

Chapter II. [Paper 1]

Chapter III. [Paper 2]

Chapter V. [Paper 4]

I. Introduction

1. Motivation

In most developed regions of the world, electric energy systems are in the midst of a fundamental transformation. Traditionally, electric energy systems followed a hierarchical top-down design: A limited number of large conventional power plants produced energy to feed the transmission grid, which, in turn, was designed to distribute energy to consumers. Political will, tremendous advancements and consequently a steep decline in the cost of renewable energy technologies have led to a rapid and steadily increasing deployment of technologies to use Renewable Energy Sources (RES). Electrical energy consumption has almost quadrupled between 1973 and 2014 (IEA 2016) and is estimated to increase by another 30% by 2040 (U.S. EIA 2016). Meanwhile, the share of electricity consumption covered through RES has increased to nearly 22% in 2012 and is expected to grow by around 3% p.a. in the years to come (U.S. EIA 2016). Hence, the total share of electrical energy consumption covered through RES is expected to range between 30% and 40% in 2040 (U.S. EIA 2016 and IEA 2017), with some countries such as Germany aspiring to reach levels above 65% (BMWI 2016). Photovoltaic (PV) generation has become a major source of low-carbon energy generation capacity in China and India. Wind power is expected to become the leading source of electricity in the European Union soon after 2030 due to strong growth both onshore and offshore (IEA 2017). In total, RES account for 80% of new capacity installed in the European Union.

In traditional energy systems, demand and supply are balanced by adjusting the controllable share of energy supply (e.g., increasing production of conventional, coal-fired power plants by activating a withheld reserve or reducing throttle valves (Panos 2009, p. 411)). The fundamental change towards a larger share of RES on the supply side has started to challenge this paradigm over recent years. Three unfavorable characteristics of RES render the management of energy systems with a high RES share a complex task (Hirth 2013; Milligan and Kirby 2009; Borenstein 2012). Firstly, electricity production from most RES is variable and difficult to control as generation depends on weather conditions (e.g., PV depends on available solar radiation). Unfortunately, the available electricity does not necessarily match electricity demand. Secondly, generation from most RES is uncertain until it has been realized, i.e. forecast errors on RES generation are systemic. Thirdly, RES are location-specific, which leads to (decentralized) distributed generation units instead of large (centralized) production plants. Balancing energy supply and demand is challenging in such an environment. However, to increase the share of energy from RES in an energy system, one must overcome these challenges and find a way to increase flexibility (Jacobson and Delucchi 2011; Kondziella and Bruckner 2016; Agora Energiewende 2017). Among different measures for increasing system flexibility, Demand Response (DR) in combination with Electric Energy Storages Systems (EESSs) are particularly promising since these measures can reduce the need for expensive peak power technologies on the supply side tremendously (Delucchi and Jacobson 2011; ENTSO-E 2014; Tveten et al. 2016; Lund et al. 2015; Smart Grid Task Force 2015). More specifically, industrial, commercial, or residential consumers can combine their available consumption flexibility potential with distributed generation units or EESSs.

EESSs play a strategic role in integrating high levels of RES into energy systems. A recent meta-study on worldwide EESS expansion plans has come to the conclusion that the demand for energy storage systems will increase linearly in terms of power capacity, and exponentially in terms of energy capacity with a growing share of distributed RES generation units (Cebulla et al. 2018). Despite their strategic value, the worldwide use of EESSs is still in its infancy due to high investment costs and short lifetimes as a consequence of heavy wear (Pierpoint 2016). Thus, one of the main objectives for operating EESSs is to define the operational schedule for charging and discharging the EESS and related components in a way that ensures a cost-effective, resource-efficient, and reliable energy system (Chauhan and Saini 2014).

2. Research design

This cumulative dissertation investigates the operation of storage-augmented energy systems and their interaction with the overall energy system. A storage-augmented energy system, in this context, is defined as an EESS in close proximity to consumers and distributed generation units under joint control. The following chapters of this work reflect four papers published in scientific, peer-reviewed journals and conference proceedings that aim to answer the following Research Questions (RQs; see also Figure I.1):

FF5: *What is the status of research of mathematical decision support models for operating storage-augmented energy systems?*

FF6: *How do thermal and electrical energy storage systems in hybrid energy systems influence each other, and how does their interaction influence the way the superordinate system should be operated?*

FF7: *Which models are suitable to include battery aging costs into the operation problem, and how does this cost-factor change the way the storage-augmented energy system should be operated?*

FF8: *To what extent does including an EESS into an industrial production facility enhance the flexibility offering to the overall energy system?*

All four publications focus on various combinations of the above RQs, and apply different research methodologies to address them (see also Figure I.1).

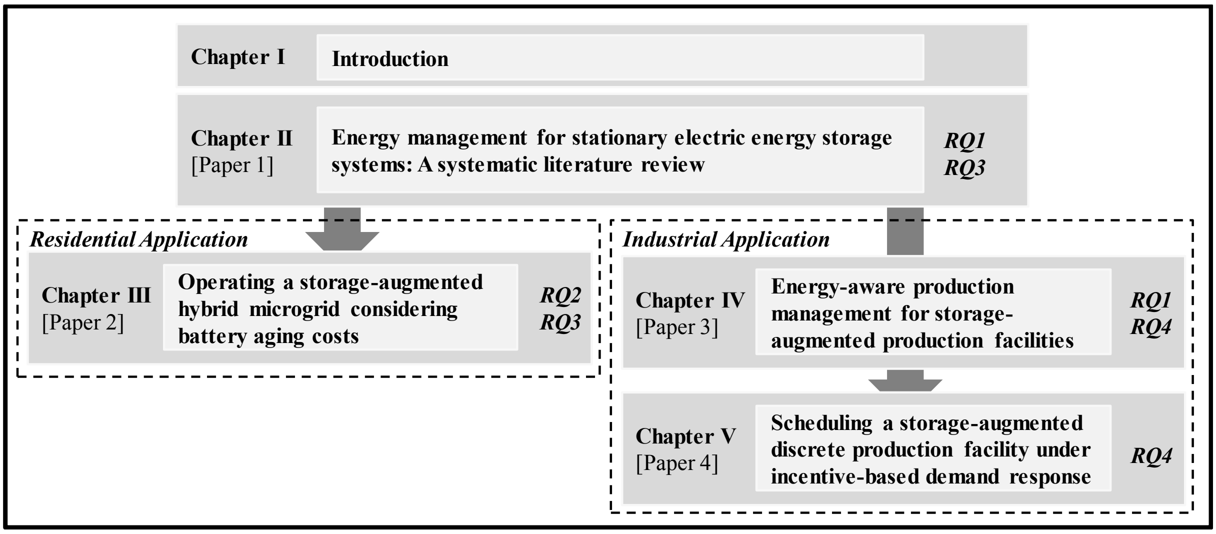

Figure I.1: Research design and structure of the dissertation

Chapter II begins with a systematic and comprehensive literature review on the current status of research of energy management for storage-augmented systems in stationary applications. The chapter first develops a conceptual framework, which is then used to structure and discuss the relevant literature. Chapter II concludes with a set of propositions for future research based on the identified research gaps, and hence prepares Chapters III to V. Chapter III and Chapter V develop mathematical models for operating storage-augmented energy systems in residential and industrial applications, respectively, and discuss the results of computational studies on exemplary configurations. Chapter IV, in contrast, formulates a conceptual framework on demand-side flexibility measures in industrial production facilities as a preliminary work for Chapter V. In the following, the different research areas of Chapters II to IV are outlined in more detail, and the specific research gaps addressed by the four chapters are explained.

The systematic and comprehensive literature review presented in Chapter II develops an overall view on the current status of research in the field (RQ1). Chapter II provides an introduction to energy management of EESSs in general, and the multifarious aspects to be considered when operating stationary systems in particular. Research in this field has received more and more attention in recent years. The vast amount of publications on the management of EESSs, especially in the last ten years, has created a need for a structured review and classification of existing research. Although several papers reviewing the matter have been published (Iqbal et al. 2014; Bazmi and Zahedi 2011; Fathima and Palanisamy 2015; Rahman et al. 2015; Chauhan and Saini 2014), the review in Chapter II differs from existing research in terms of its focus on mathematical models and its systematic review approach. In the synthesis of the reviewed publications, Chapter II outlines propositions for future research, which were partially addressed in Chapters III to V. As one example, it became evident that usage-related cost models for storages were underrepresented in the sample (RQ3), covered in Chapter III.

Chapter III analyzes operations of a storage-augmented, hybrid residential microgrid. The chapter contributes to research by investigating the case of a Hybrid Integrated Local Energy Supplier (HILES). The HILES is responsible for meeting local hybrid, i.e. electrical and thermal, energy demands while interacting with the grid at real-time pricing and participating in a price-based DR program. The attraction for the HILES arises from efficiently using non-renewable decentralized generation units by leveraging Thermal Energy Storage Systems (TESSs) and EESSs. Compared to classical, thermal power plants, distributed generation units utilize primary energy resources more efficiently as they offer the opportunity to use excess heat to serve local thermal demand. Gas-fired Combined Heat and Power plants (CHP) can operate at combined efficiencies ranging between 70 % and 80 % (Cho et al. 2014). This is well above the efficiency levels of conventional power plants without waste heat utilization that usually do not exceed 30 % (EPA 2015). Besides the aforementioned challenges associated with generating electricity from RES, thermal and electrical energy demand in hybrid systems are for the most part uncorrelated, whereas combined generation units generate thermal and electrical energy simultaneously in a fixed ratio. Therefore, in practice, combined generation units follow either electrical or thermal loads when operated heuristically (Li et al. 2015; Mago et al. 2009). Two approaches have been applied in Chapter III to respond to these challenges. On the on hand, optimization methods support economic and reliable operations of Microgrids (MGs) and have already attracted much attention among researchers and practitioners in recent years (Fathima and Palanisamy 2015; Theo et al. 2017). On the other hand, hybrid energy storage systems, a combination of EESSs and TESSs, can be applied to decouple both types of demands. Chapter III first contributes to the research by revisiting current work on optimization models for MG that include Battery Energy Storage Systems (BESSs) and take battery aging into account, either directly or indirectly (RQ3). Most of current research has focused on using BESSs to optimize energy systems for economic, ecological, and technical objectives, but barely considered battery aging in the optimization models. Especially battery aging models that consider specific usage conditions have been underrepresented. Chapter III addresses this research gap by deriving a weighted cost model, considering both cyclical and calendrical aging components, from the domain-specific literature on battery lifetime prediction. The Chapter further integrates the piecewise-linearized battery aging model into a Mixed Integer Linear Programming (MILP) formulation for a hybrid MG application. The influence of the battery aging model formulation on MG operations in a cost-optimal schedule is illustrated in a computational study for a real-world example. Secondly, Chapter III contributes to research by investigating the interdependencies of the thermal and electrical systems in a parameter study on component sizing. Sensitivities are investigated through selected key parameters and show that BESSs and TESSs can significantly reduce the grid-provided energy without losing economic viability.

Chapter IV and Chapter V put the spotlight on the industrial consumer. By size, the industrial sector was responsible for around 42.5% of world-wide electricity consumption in 2014 (IEA 2016). This entails a large potential for generating flexibility by demand-side management (Paulus and Borggrefe 2011). Chapter IV addresses research efforts undertaken to tap this potential and to enable industrial consumers to offer short-term flexibility. Based on the work of Gahm et al. (2016), Chapter IV fosters the idea that production facilities (PF) incorporate a versatile set of flexibility measures that enable them to modulate their electricity consumption time- and volume-wise and, as a result, to participate in respective flexibility markets. Chapter IV develops a conceptual framework for an energy-aware view on production facilities to identify the various resources of flexibility. Besides the production system, whose energy consumption is adjustable by changing the production schedule (Graßl and Reinhart 2014), there are many examples for additional resources of flexibility such as local generation, energy conversion systems, and other auxiliary systems, of which many show a storage-equivalent behavior. As a final note, the chapter proposes a control architecture to coordinate the different sources of flexibility.

Chapter V elaborates on the ideas outlined in Chapter IV and presents an in-depth analysis of a storage-augmented industrial PF participating in DR. For simplicity, this work concentrates on the production system and a co-located BESS. Chapter V outlines challenges for industrial consumers participating in DR and provides an overview of the corresponding literature. For residential and commercial consumers, interdependencies between the scheduling of different applications (e.g., refrigerators or air conditioning equipment) are negligible and scheduling can be performed independently. Prior research has investigated various residential applications and to what extent they are compatible with DR, e.g. for air conditioning, cloth dryers, or dishwashers (Yoon et al. 2014; Chen et al. 2012). For industrial consumers, however, participating in DR is more difficult as the scheduling of processes within facilities is often subject to many interdependencies. An invariant sequence of production process steps, for instance, prevents the independent rescheduling of individual tasks. While in many traditional DR programs, system operators require direct control of single consumers for short-term flexibility, the aforementioned complexity within industrial consumers falsifies the appropriateness of such approaches and reveals the need for other solutions. In industrial applications, DR thus requires sophisticated models that account for the influence of DR on production processes and vice versa. Firstly, Chapter V contributes to this research by proposing an incentive-based program according to which the facility operator determines alternative electricity consumption scenarios and communicates discrete load reduction potentials to the system operator without disclosing internal processes. Secondly, Chapter V develops a flexible flow shop formulation for a discrete manufacturing process based on the work of Chung-Yang and Shi-Chung (2000). The reference model is extended to account for the operating-mode-specific energy consumption of machines with specific consumption trajectories per product-machine-combination. A MILP formulation is suggested to model and solve the problem in three stages. First, a baseline solution is developed by minimizing total weighted completion time. Then, based on the baseline solution, additional solutions with different responses to the DR are calculated and a load reduction curve as a potential means of communication is established. Finally, the effects of using a BESS to allow easy-to-apply and economically better responses are studied. A numerical example is provided and analyzed to give a zest of the suggested solution.

The contribution of this dissertation on operating storage-augmented systems is threefold. Firstly, a comprehensive and systematic literature review on optimization of energy management of storage-augmented systems (Chapter II) was outlined to direct motivated researchers into new and less researched areas for the future. Secondly, two decision support models, one for operating a residential microgrid with special focus on battery aging costs (Chapter III) and a second one to enable industrial production facilities to contribute flexibility more effectively and efficiently (Chapter V) were derived. Thirdly, a conceptual framework for an energy-aware view on production facilities (Chapter IV) was presented. Throughout Chapter III to V, real-world applications are kept in focus, and at the end of each chapter, managerial implications are presented to enhance further dissemination under given limitations. Hopefully, this dissertation will contribute to the smooth and ongoing transformation of our energy systems with the increasing penetration of RES.

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II. [Paper 1] Energy management for stationary electric energy storage systems: A systematic literature review[1]

Abstract

Electric Energy Storage Systems (EESSs) have received an increased attention in recent years due to their important role in an active management of energy supply systems. Fueled by the increasing shares of intermitting Renewable Energy Sources (RES) in today's energy supply, balancing energy demand and energy supply over time becomes more and more challenging. EESSs are recognized as a key technology to overcome this challenge by storing energy and converting it back when needed. Even though some EESSs solutions are already available on the market, EESSs suffer from technical limitations and entail high investment costs. Energy management is responsible for managing the operations of EESSs and the interactions with the surrounding systems. An optimal energy management is an important precondition to ensure economic viability of EESSs. This chapter presents a systematic review of the literature on energy management for stationary EESSs applications. The aim of the chapter is to give a comprehensive overview of the literature in this field and to develop a conceptual framework that facilitates the structuring of research on the management of EESSs and the identification of future research opportunities. The chapter first introduces the methodology used for the literature review and then descriptively analyzes the identified publications. Afterwards, it outlines the proposed conceptual framework that provides a structure for categorizing the identified literature. Subsequently, we discuss the identified papers in light of the proposed framework. The chapter then concludes with a discussion of future research opportunities.

Keywords:

Electric Energy Storage Systems, Energy Management, Optimal Policy, Optimal Strategy, Optimal Scheduling, Solution Techniques, Literature Review

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III. [Paper 2] Operating a Storage-Augmented Hybrid Microgrid Considering Battery Aging Costs[1]

Abstract

Over the last decades, electricity demand and supply have become more decentralized, and the opportunities for locally managed microgrids have increased. Especially for residential microgrids consisting of multiple residential buildings equipped with a substantial share of local thermal and electrical energy production, flexibility is needed to balance energy demand and energy supply over time. Battery energy storage systems (BESSs) and thermal energy storage systems can provide this flexibility. Even though some BESS solutions are already available on the market, BESS still suffer from technical limitations and entail high investment costs. As BESS deteriorate over time depending on usage characteristics and the surrounding conditions, actively managing these parameters will largely affect their potential lifetime and the economic viability of their application. The majority of current research has focused on using BESS to optimize energy systems for economical, ecological, and technical objectives, but barely considered battery aging in the optimization models themselves. To contribute to closing this research gap, this chapter proposes an optimization model for the optimal day-ahead management of a multi-building district considering battery aging costs (BAC) derived from specific literature on battery degradation mechanisms. The resulting non-linear model is linearized and solved by using a commercial solver. Computational studies are performed to illustrate the case of a hybrid integrated local energy supplier responsible for the multi-building district, and sensitivities of its operating profits towards different sizing and pricing parameters are investigated. Results confirm the importance of considering BAC in decision support models for managing energy systems, both for a cost-efficient management of battery operations and to improve battery lifetime. The results also indicate that the application of BESS in day-ahead markets are only relevant for future cost levels of the technology.

Keywords:
Battery Energy Storage, Battery Aging Costs, Hybrid Microgrid, Thermal and Electrical Supply, Scheduling Problem, Mixed Integer Linear Programming

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IV. [Paper 3] Energy-Aware Production Management for Storage-Augmented Production Facilities [1]

Abstract

The last decades have witnessed a fundamental change in electricity supply and demand across the world. While both energy generation and consumption have increased worldwide by around 50% between 1993 and 2012, the share of renewable energy in the total amount of energy supply has increased as well and is expected to grow further in the years to come. The highly distributed allocation and the hardly controllable intermittency of renewable energy resources strongly contrast with traditional energy generation, and thus create major challenges for the management of present and future energy systems.

The most relevant challenge today is that energy generation from renewable sources only rarely matches energy demand over time. As a result, modern energy systems need flexibility in managing differences between energy generation and demand. Industrial production accounts for a large share of the total energy consumption and more and more becomes a source of renewable energy generation itself. Airbus and Tesla, for instance, equipped their new production facilities with a substantial amount of renewable energy generation facilities whose energy generation often exceeds internal consumption.

Industrial production has potentials for flexibility by actively managing its energy demand over time. Thus, production and production management should not be considered a simple, non-controllable load in the future, but rather an active member of the overall energy system. However, centrally controlling the production facility for short-term flexibility operation may become computationally infeasible. For this reason, this chapter proposes a framework that proposes a distributed control arrangement. The framework considers five subsystems of components in industrial production facilities: the production system, auxiliary systems featuring production-bound and unbound systems, energy conversion systems and local energy generation systems. Each subsystem is equipped with a local flexibility controller and coordinated by a central controller.

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1. Introduction

Over the last decade, energy systems have experienced a fundamental change towards a significant share of energy originating from renewable, intermitting sources (U.S. EIA 2015). As a result, maintaining the balance between electricity supply and demand has become a complex task in modern energy systems, and ensuring system stability is no longer the responsibility of the supply side alone. Demand Response (DR) leverages flexible loads on the demand side to provide needed balancing power (Albadi and El-Saadany 2008; Aghaei and Alizadeh 2013; Siano 2014; Keane et al. 2011; Haider et al. 2016), and it is becoming one of the main pillars for the smart grid paradigm. Flexibility is the technical ability of a load to adapt its consumption when needed. DR embraces the flexibility by price-based and incentive-based programs. Price-based programs aim to influence the electricity consumption pattern of end-users through electricity prices that change over time. In contrast, incentive-based programs resort to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized (U.S. DoE 2006).

For adopting short-term DR measures (e.g. within an hour), the system operator is often permitted to directly reschedule, reduce, or disconnect loads to prevent critical periods, when the stability of the power grid is at risk. However, the direct control of loads by a third party interferes with consumer privacy and internal operations and it may prevent consumers from participating in DR. Other solutions that would enable timely load adjustments, but that do not require direct access to loads, could therefore lead to a higher DR potential.

Industrial consumers and in particular their Production Facilities (PF) are of special interest for DR research for three reasons. Firstly, around 42.5% of world-wide electricity consumption could be accounted to industrial usage in 2014 (IEA 2016). Due to this high share in the total energy consumption, this group of consumers has a particularly high potential for DR. Secondly, industrial consumers bear a large potential for flexibility in load management in their complex and large organizations (Paulus and Borggrefe 2011). Thirdly, tapping these potentials requires a deep interference with internal operations, which requires advanced communication and coordination techniques often available in PF.

This chapter supports tapping industrial PFs' potential for offering its short-term flexibility to system operators. To this end, this work formulates a framework for researchers to identify participants and structure decision problems for better handling complexity within distributed control arrangements.

2. Development of the framework

Based on the work of Gahm et al. (2016) on decision-relevant subsystems in a PF for energy planning and based on own considerations, we developed the framework described in this section as an integrated, energy-aware view on PF for offering its short-term flexibility (see Figure IV.1). PF include various elements starting from production systems itself back to local energy generation facilities that contribute to short-term energy flexibility, which will be described in the following.

The Production System (PS) (see Figure IV.1), at the center of a PF, may contribute to flexibility through various measures. Since energy consumption varies across different production stages and across machines at the same stage, the total energy consumption is controllable, firstly, either by adapting the sequence of jobs or by changing the allocation of jobs to machines at any of the stages. Secondly, delaying individual production steps or even interrupting on-going processes can further change total energy consumption (Graßl and Reinhart 2014). In addition, in continuous production processes, adapting process parameters (such as the production rate or processing temperature) might significantly influence energy consumption. Changes of the production schedule, however, influence inventory levels and throughput times. Physical inventories would become equivalents to energy storages in this case. In recent years, energy-aware production planning has become increasingly popular and thus, besides traditional production planning objectives, energy-related objectives such as energy consumption, energy costs or greenhouse-gas emissions have more and more attracted the attention of researchers and practitioners (Biel and Glock 2016; Gahm et al. 2016). Li and Hong (2017), for example, presented an algorithm for a market-based DR program in a discrete manufacturing facility. For a given incentive for load reductions, the proposed algorithm reschedules the production plan to lower energy consumption in the respective period. As a result, production output is lowered and the tradeoff between revenue from production and provided flexibility is optimized. Another example of providing flexibility in the PS is presented in Keller et al. (2016).

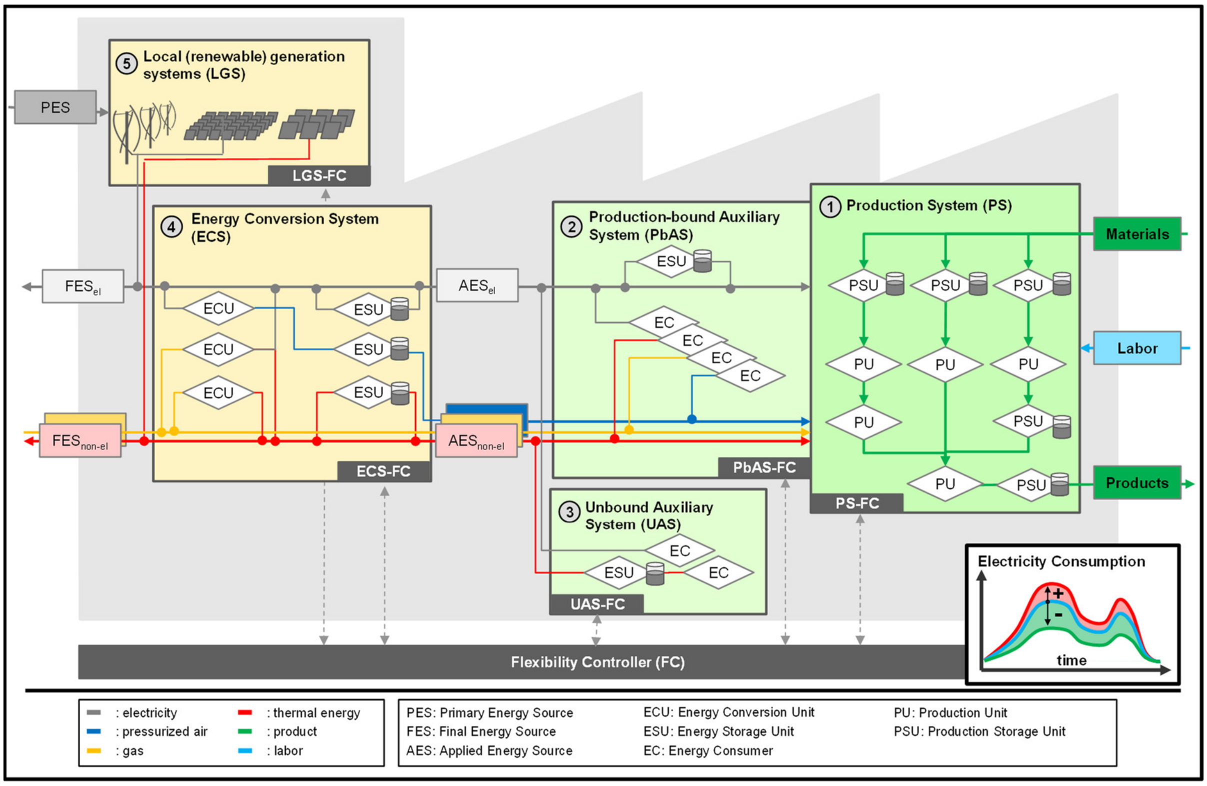

Figure IV.1: Flexibility controller in an energy-oriented PF

Next to the PS, we group all auxiliary processes with local consumers that are not part of the PS and not related to the main production process. In this group, we distinguish between Production-bound Auxiliary Systems (PbAS) and Unbound Auxiliary Systems (UAS) (see Figure IV.1). This differentiation is useful as units in PbAS depend on the schedule of the PS, and determining flexibility in PbAS requires knowledge about the production schedule. UAS, in contrast, can be managed independently of the PS. An example for PbAS are electric vehicle (EV) fleets in intralogistics. Runge et al. (2014) investigated the flexibility potential of infrastructure for charging the EV fleet at a container terminal. The EV fleet runs with additional battery-charging stations; the state-of-charge of the batteries and their availability at the charging stations depend on the schedule for unloading ships. Studying the charging of batteries and the unloading of ships independently might thus result in infeasible solutions.

EV fleets, however, can also be considered independent of the production process and thus be part of UAS (see Figure IV.1). Beier et al. (2016), for instance, investigated the role of the electric storage capacity of an (employee-owned) EV fleet available for charging to compensate mismatches between supply from local renewable energy sources at a discrete manufacturing line. In comparison with similar stationary batteries, EV fleets offer some advantages as they do not need additional investments and offer an alternative use in traction applications. A further example of UAS are heating, ventilation and air-conditioning systems of the PF which typically allow modification without affecting their thermal service due to thermal inertia of the entire system (Bruninx et al. 2013).

The fourth and fifth subsystems we identified for providing energy flexibility are internal Energy Conversion Systems (ECS) and Local (renewable) Generation Systems (LGS) (see Figure IV.1). We distinguish between three sources of energy. Most valuable to the PF are applied energy sources, such as electricity, gas, pressurized air, and heat, which can directly be used in the PS. Some of these energy sources are not grid-bound and need to be converted from final energy sources such as electricity and gas in the ECS beforehand. Primary energy sources such as wind and solar energy are converted into electricity in the LGS beforehand. Nevertheless, both systems offer flexibility potential either through internal storage potentials or, in the case of LGS, by simply curtailing production. One example for energy conversion units are combined heat and power plants that convert gas into heat and electricity. Another example is compressed air which is converted from electricity by compressors. Pressurized (air) tanks can additionally be used as storages. An integrated ECS and PS control strategy using compressed air to increase self-sufficiency of a PF with local RES was presented by Beier et al. (2015). By means of a combined control of compressed air production and PS, the authors were able to improve the self-sufficiency ratio by around 6 percentage points through an adequate sizing of a compressed air tank. When combined with a gas turbine, pressurized air can be converted back to electricity. The overall efficiency of the converting electricity to compressed air and back to electricity, however, is rather low compared to battery technologies and additionally, further investments would be required. Feng et al. (2016) formulated a similar optimization problem for the complete ECS.

Centrally controlling the PF for short-term flexibility may suffer from long model development time and huge computational efforts due to many interdependencies. We suggest a distributed control arrangement with decentralized flexibility controllers for each of the subsystems described above and a central flexibility controller taking the role of a market maker coordinating the other subsystems. An example concentrating only on PS can be found in Zou et al. (2017). The authors presented a distributed control arrangement for a continuous manufacturing system. To handle complexity, every machine in the serial production line has a local controller following a cost function including local costs at machine-level and collaborating costs induced from surrounding and affected machines. To set priorities in solving the control problem between local controllers, the problem is solved iteratively starting with the slowest machine.

The above mentioned concept can be applied at the PF level. The decentralized flexibility controllers determine local flexibility potential. The central flexibility controller collects information on flexibility potential and coordinates decentral, subsystem flexibility controllers in multiple iterations to generate an efficient and feasible, but not necessarily optimal solution. Additionally, the central flexibility controller communicates the monetary flexibility offer to the system operator and implements control inputs in case offers are accepted.

3. Outlook

Energy consumption and an active participation in grid operations have become topics of interest in today's management of production facilities. This paper introduced a framework for an energy-aware view on PF to manage flexibilities with a distributed control arrangement. In future research, we will further detail operations of the decentral subsystem flexibility controllers units and how their interaction with the central flexibility controller should be organized.

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V. [Paper 4] Scheduling a Storage-Augmented Discrete Production Facility under Incentive-based Demand Response [1]

Abstract

Demand Response is considered one of the most important measures for balancing energy supply and demand in the smart grid paradigm. Incentive-based Programs, one manifestation of Demand Response, contribute to short-term system stability and prevent critical periods when system stability is at risk by enabling the system operator to directly change total energy demand. The fact that a third party would be empowered to interfere with internal operations is, however, also one of the major drawbacks of Demand Response that prevents especially industrial consumers from participating with full capacity in such programs.

This chapter considers an alternative Incentive-based Program with application to a discrete manufacturing facility where load reduction curves are generated a priori outlining the potential load reduction in the Demand Response period. The system operator uses the load reduction curves to determine the desired level of load reduction for critical periods. To illustrate the generation of the load reduction curves, this chapter builds on a Flexible Flow Shop formulation for a discrete manufacturing facility and presents a model that includes multiple machine modes and product- and machine-specific energy consumption trajectories. Based on the flexible flow shop, a procedure is developed to generate the load reduction curves. The chapter also investigates the potential of including a battery energy storage system into the production facility and illustrates the effects of the battery energy storage system on the load reduction curves.

Keywords:
Mixed Integer Linear Programming, Flow Shop Scheduling, Flexibility, Energy Management, Energy Optimization

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